HHS Public Access

Author manuscript

Spinal Cord. Author manuscript; available in PMC 2012 October 01.

Published in final edited form as:

Spinal Cord. 2012 April ; 50(4): 309–314. doi:10.1038/sc.2011.123.

Postural bipedance in paraplegics under Neuromuscular Electrical Stimulation: Is it possible to improve it based on Sagittal Spinal Alignment?

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Abstract

Study design—Experimental trial based on the analytical study of the radiographic standards of the sagittal spinal alignment in paraplegics in upright position under surface Neuromuscular Electrical Stimulation (NMES).

Objectives—To evaluate changes in radiographic standards of the sagittal spinal alignment of paraplegics under three different models of NMES used to optimize the global bipedal posture.

Setting—The University Hospital Ambulatory (UNICAMP), Campinas, SP, Brazil

Methods—Ten paraplegic patients were selected. Each patient underwent three different models of NMES. The influence that each NMES models exerted over the sagittal balance of the spine was evaluated by lateral panoramic x-rays. Wilcoxon's Test was used to compare the modifications observed in each NMES model in the group studied.

Results—Using the femoral quadriceps muscles' NMES as the starting point, the inclusion of the gluteus maximus' NMES generated an increase of the lumbar lordosis and an decrease of the spinal tilt angle. These alterations resulted in partial improvement of the anterior sagittal imbalance. NMES of the paralyzed paravertebral lumbar muscles resulted in a more expressive increase on the lumbar lordosis with no important change on the spinal tilt. On the latter model, however, an improvement of 20% was observed in the global sagittal imbalance due to a posterior translation of the spine as pointed out by the decrease in the C7-HA horizontal distance.

Conclusions—The proposed NMES models were able to partially amend the anterior sagittal imbalance of the paraplegic patients in bipedal posture.

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Conflict of interest: The authors declare no conflict of interest.

Keywords

Spinal cord injury; Paraplegic standing; neuromuscular electrical stimulation; sagittal spinal alignment

Introduction

The body balance in neurologically normal people in the standing position is given by the segmental postural reflexes which are integrated in the spinal cord and modulated by higher neural centers[1]. Since two-thirds of the entire body mass is located above the hips[2], the main primary postural reflexes regulate the spinopelvic sagittal balance to maintain a close relationship between the gravity center and the perimeter of body support given by the feet with minimum energy expenditure [3]. The segmental postural reflexes below the spinal cord injury are absent in paraplegics. Potten[4] and Seelen [5] observed that in these subjects the loss of function of the erector spinal muscle is partially offset by the increase of the electromyographic activity and hypertrophy of the muscles latissimus dorsi and upper third of the trapezius. Several functional rehabilitation programs aim at improving the posture in paraplegics by stimulating the affected muscles. The simplest way to obtain the upright position in these patients is the open loop neuromuscular electrical stimulation (NMES) of the knee extensors complemented by manual support. Matjacic and Bajd[7] proposed a hands-free strategy to control the bipedal posture in paraplegics. Their theory was based on a mathematical model of an interconnected double inverted pendulum which ignores the mobility and shape of the spine and considers the entire body segment above the hips as a single rigid structure. Unfortunately, until now no NMES system has been able to eliminate the need of manual support to keep the body balance and the human functional upright posture. More recently, Castro de Medeiros *et al*.[8] described the radiographic parameters of sagittal spine balance in paraplegics in bipedal posture under NMES of knee extensors with a significant anterior sagittal imbalance associated to an inverted pelvic tilt not compensated by any spinopelvic mechanism and counterbalanced by the upper limbs only. Currently, activation of lumbar paravertebral muscles in paraplegics has been used in two lines of research: the Neuromuscular Electrical Stimulation, which has the goal of improving the functional performance of seated paraplegics [9] and the intercostal neurotization for the lumbar muscles [10]. It is believed that in paraplegics the control of the spinopelvic balance is of paramount importance to obtain a functional bipedal posture. So to understand better the subject we described and compared the NMES spinopelvic radiographic changes of the main muscles involved in this process with the paraplegics in bipedal posture.

Materials and methods

Ten paraplegic male adult subjects were used, all with ASIA Scale motor score of 50. Their neurological level ranged from T6-T10 with car accident being their main cause of injury. Their average age was 36.6 years; average weight 81.6Kg and average sitting height 92.6cm. All of them had a history of more than six years of paraplegia and were involved in a rehabilitation program with neuromuscular electrical stimulation for at least one year (Table 2). Prior to the start of the study all subjects gave their written informed consent in accordance to the Helsinki Declaration and approved by the local Ethics Committee. Subjects were selected from the medical records and imaging exams among those actively participating in the NMES walking rehabilitation program at the Spinal Cord Injury Rehabilitation Ambulatory, Department of Orthopaedia and Traumatology, Campinas State University (Unicamp) Hospital, SP, Brazil. The inclusion criteria were: complete paralysis; absence of scoliosis and pelvic obliquity; absence of visual or vestibular comorbidities and capacity of walking with NMES. Classical orthopaedic physical examination discarded bone deformities and muscle shortening and joint x-rays were obtained for exclusion of heterotopic ossification that limited the motion arcs of the hips and knees. The spasticity was assessed by applying the modified Ashworth Scale. Criteria of the American Spinal Injury Association (ASIA) were used to define the neurological level and to quantify the total residual neurological function[11]. The seated height was measured from the ischium to the skull vertex with the patient in the supine position and his/her hips and knees flexed in 90°. Each patient underwent three sequential NMES electrode configurations (EC): 1: quadriceps; 2: quadriceps + gluteus maximus; 3: quadriceps + gluteus maximus + paravertebral muscles below the injury and at 3cm from the midline. NMES parameters were: steady voltage; 300μs rectangular pulses; 25 Hz frequency, 70-150V amplitude and measured with 1 Kohm load resistor. AFO-type orthesis were used together with open loop transcutaneous NMES complemented by bimanual hand support. Clinically, all subjects were plantigrade with extended knees. Aiming to optimize their fatigue endurence, all subjects underwent prior training of the muscle groups described above twice a weed for eight weeks.

Three lateral panoramic x-rays, one for each electrode configuration were taken from all subjects to evaluate the eventual influences of the different NMES ECs on the sagittal spinal alignment in paraplegics. As standard x-ray procedure, a long chassis with a film of 36.5cm × 91cm remained at a fixed distance of 230cm from the radiation source allowing exposure from the base of the skull to the proximal third of the femurs. Subjects were placed in a standing position with NMES complemented by a bimanual hand support so that the right shoulder was left towards the chassis and the face looking straight ahead. To reproduce the postural adjustments preceding the start of a paraplegic gait, a bimanual hand support was placed at variable distances and heights and adjusted to the balance needs of each subject. To keep the subjects in the same posture, the flexion angle of the upper limbs with the vertical axis of the body was set at 25° as recommended by previous studies[17]. A conventional goniometer was used while the x-rays were being taken. With the subjects standing under the EC 1, the NMES of the gluteus maximus and the lumbar paravertebral muscles were sequentially activated by short periods of time (average: 20 seconds) as necessary just to obtain the x-rays. Each x-ray film was measured twice at different moments with the averages used as base for each patient. The resulting data were organized in three categories: 1: spine sagittal profile; 2: pelvis attitude and 3: spinopelvic balance (Figure 1 and Table 3). The kyphosis and the plumb line previously found anterior to the upper posterior corner of S1 were represented by positive values while negative values indicated lordosis and a plumb line posterior to the upper posterior corner of S1.

All average values and standard deviations were calculated from data generated in the three ECs of NMES. The Wilcoxon test was used to counterbalance the influence from the different ECs on the sagittal spine alignment with the values being considered statistically significant when simultaneously presenting $T < 8$ and $p < 0.05$.

Results

All x-rays measurements of sagittal alignment from upright paraplegic patients under three different NMES ECs are in Table 3. The comparative analysis of the radiographic evaluation of the sagittal balance of the spine between the three NMES electrode configurations suggests, in a statistically significant way (Table 4) are:

1) EC 1 compared to EC 2: the addition of NMES to the gluteus maximus caused posterior rotation of the Pelvic Tilt (−4°) and of the Sagittal Tilt (−4.2°), increased lordosis L5-S1 (−3.9°), increased lordosis by the pelvic radius technique PR-T12 (−1.3°) and decreased the horizontal distance T4-HA (−3.1cm).

2) EC 2 compared to EC 3: the addition of NMES to the paravertebral muscles decreased the distance C7-S1 (− 8cm) and increased lordosis L1-S1 (−18.5°).

3) EC 1 compared to EC 3**: s**imultaneous NMES of the gluteus maximus and lumbar paravertebral muscles increased lordosis PR-T12 (−7.7°), increased the sagittal tilt angle (−4.3°), decreased the distance C7-HA (−3.8cm) and T4-HA (−3.3cm) and decreased the T4-T12/T12-PR ratio.

Discussion

Studies on healthy volunteers describe the spinopelvic interrelations as major controllers of the spine sagittal balance and of the body gravity line[12-15]. Schwab *et al*.[15] analysed the sagittal balance and the gravity line and concluded that every spinopelvic compensation has as its ultimate goal maintaining the gravity centre in close relationship with the feet positioning. According to Van der Spek *et al*.[16] the degree of stabilization of the hips and the distance of the position of crutches to support paraplegics lacks statistically significant influence both on the posture adopted by patients and on the force applied to the crutches while allowing a stable orthostatic posture. These authors still suggest that the flexibility of the spine and the effect of the lumbar paravertebral muscles are fundamental to postural stability and load-bearing and that new study models should include these variables to optimize the control of the postural balance. Analyzing the sagittal spinal balance of spine injured patients with NMES applied to the quadriceps, Medeiros *et al*.[8] described a pattern characterized by apparently fixed flexion of the hips, sagittal curvatures of the spine presenting “normal values”, but not offsetting the pelvic effects and large anterior sagittal imbalance which was supported by the upper limbs. In this study, all patients submitted to NMES of just the quadriceps (EC 1) showed the sagittal pattern as described above (figure 2 A).

In an attempt to optimize the position of the paraplegics’ gravity line seen in the EC 1, we proposed two experimental models of NMES that try to reproduce the spinopelvic compensations described in the literature.

Lieberman *et al*.[17] reiterated that the anatomy of the thoracolumbar fascia/erector spinae/gluteus maximus work together to achieve extension of the spine. In addition, it is known that previous sagittal imbalances are usually offset by retroversion of the pelvis (pelvic tilt) from the extension of the hips. However, according to Roussouly *et al*.[14] no correlation was found between the positions of the C7 plumb line and the line of body gravity, the latter being related to the spinal tilt, regardless of the value of the sacral slope. To push back the anterior sagittal imbalance observed earlier in patients undergoing NMES EC 1 we applied NMES to the bilateral gluteus maximus (EC 2) in order to roll back both the pelvic and the spinal tilts. The NMES of the gluteus maximus decreased the sagittal tilt and a 22% average improvement over previous sagittal imbalances represented by the decrease in the horizontal distance T4-HA (Figure 2B). This may have resulted from a higher tension generated on the thoracolumbar fascia exerted by the contraction of the gluteus maximus.

In EC 3, NMES was added to the paralyzed paravertebral lumbar muscles to increase lumbar lordosis, obtain maximum roll back of the spinal tilt and to improve the positioning of the gravity line. In this situation lumbarsacral lordosis increased 18.5° in average (relative to EC 2) with roll back of the sagittal tilt and 3.8cm posterior translation (19,4%) of the C7-HA horizontal distance from EC 1 (Figure 2C).

The electroneuromyography by Lyons *et al*.[18] in healthy volunteers showed that the hip extension moment results from the contribution of the gluteus maximus' lower portion + hamstrings + adductor magnus. Németh *et al*.[19] found the moment arm of gluteus maximus decreased when increasing the hip flexion angle. The hamstrings showed an increase in the moment arm length up to an average of 35° in hip flexion and then a decrease with increasing hip flexion angle. For the adductor magnus, the moment arm showed an increase up to 75° and then a decrease. In all three NMES models the patients kept positive sacrum-femur angles, meaning flexed hips. We expected that the gluteus maximus' NMES would be capable of extending the hips. We believe it was not possible due to the mechanical disadvantage of the short extension lever arm generated by the gluteus maximus' NMES to offset the long flexing lever arm generated by the summation of the spinal lenght + anterior sagittal imbalance + contraction of the rectus femoralis' hip-flexor portion.

The MNES configuration used was unable to correct the paraplegics' spine sagittal imbalance. However, one can suggest with some criticism that future NMES electrode configurations should include complementary channels to the hamstrings aiming at optimizing the hips' extension lever arm in such a manner as to translate the spine by the roll back of the pelvic tilt. Sixty percent of the studied subjects subjectively reported an important decrease on the strength exerted by the upper limbs while in bipedal posture under the NMES EC 3. Even though this was not measured, such a fact could have a major impact over the incidence of late shoulder dysfunction due to the overloading of the upper limbs as described in the literature[20].

Conclusion

The proposed NMES electrode configurations applied to paraplegic patients on bipedal posture allowed a partial correction of the anterior sagittal imbalance. The major compensating mechanisms observed were: 1) posterior rotation of the sagittal tilt caused by the increase of the lumbopelvic lordosis and 2) posterior translation of C7 done by the paralyzed lumbar NMES. Despite a statistically significant result obtained in this study, the same cannot be said in terms of a significant clinical improvement specifically to the posterior rotation of the pelvic tilt promoted by the hips' extension through isolated bilateral NMES on the gluteus maximus.

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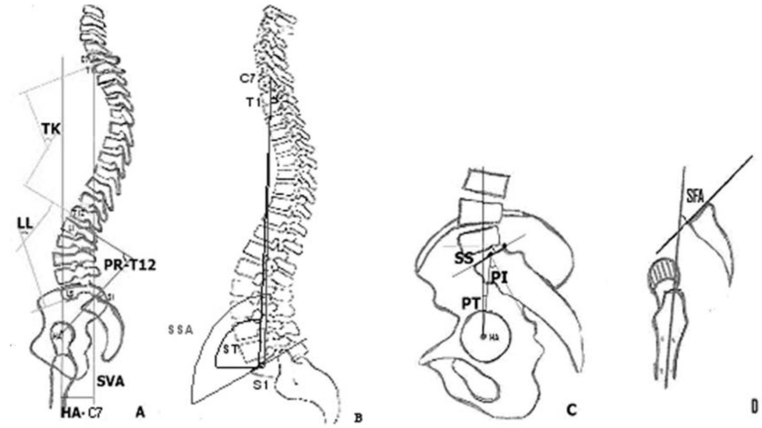

Figure 1.

A. Thoracic Kiphosis (TK) T4-T12, Lumbar Lordosis (LL) L1-L5, Jackson's pelvic radius technique (PR-T12), Horizontal distance C7 × Hip-Axis (HA-C7). B. Spinal Tilt (ST), Spinal-sacrum Angle (SSA). C. Sacral Slop (SS), Pelvic Incidence (PI), Pelvic Tilt (PT). D. Sacrum-Femur Angle (SFA).

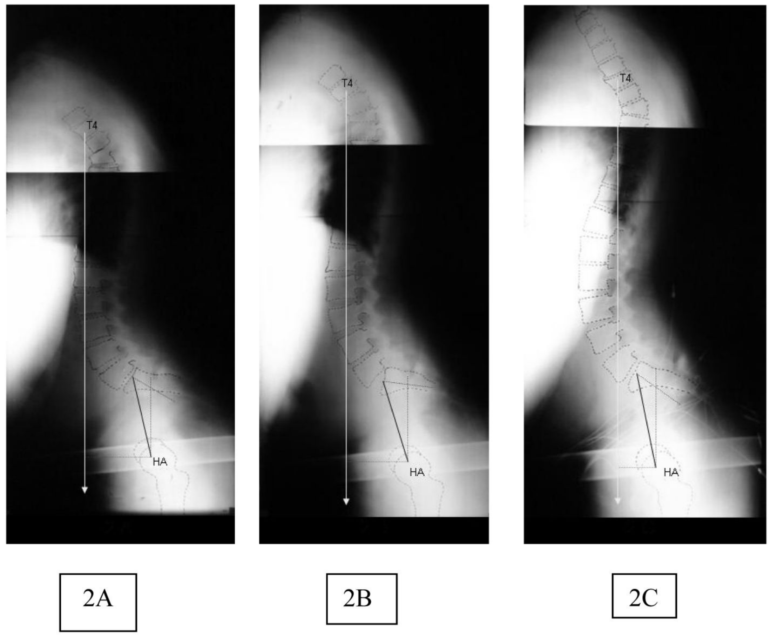

Figure 2.

Case 6 was stimulated with three differents models of Neuromuscular Electrical Stimulation (NMES). Note a progressive increase on lumbar lordosis and a decrease on sagittal imbalance (T4-HA) with the add on NMES channels. A. Femoral quadriceps NMES. B. Femoral quadriceps + gluteus maximus NMES. C. Femoral quadriceps + gluteus maximus + paravertebral lumbar NMES.

Table 1

Avaliable Parameters on Sagittal Spine Roentogenograms from Subjects

Sagittal Profile of the Spine *	Morphology and Atitude of the Pelvis * *	Spinopelvic Balance * *
Thoracic Kyphosis angle (T4 -T12)	Sacral Slop angle (SS)	Horizontal Distance (C7-S1)
Lumbar Lordosis angle (L1-L5)	Pelvic Incidence angle (PI)	Horizontal Distance (C7-HA)
Lumbosacrum Lordosis angle (L1-S1)	Pelvic Tilt angle (PT)	Horizontal Distance (T4-HA)
Segmentar Lumbar Lordosis angles: (L1-L2, L2-L3, L3-L4, L5-S1)	Pelvic Radius angle PR-T12	Horizontal Distance (T4-L4)
Ratio: Kyphosis T4-T12/ Lordosis T12-PR	Sacrum-femur angle (SFA)	Spinal Tilt (ST): (S1 Horizontal line × C7-S1 line)
		Sagittal Tilt (T9-HA line × Vertical line)
		Spino-Sacral angle (SSA): (S1 end plate line × C7-S1 line)
HA – Hip axis; PR – Pelvic Radius		

*Cobb angle measurement technique

* *according to references: 12,13,14

Table 2

General characteristics of Subjects

Patient	1	2	3	4	5	6	7	8	9	10
Gender	M	M	M	M	M	M	M	M	M	M
Age (Years)	61	33	48	26	45	22	25	33	38	35
Mass (Kg)	74	91	84	73	95	72	90	75	84	78
Sitting Height (cm)	86	89	87	96	97	92	96	93	94	96
Ethiology *	TB	FAP	auto	FAP	auto	auto	auto	auto	auto	auto
Neurological Level	T10	T7	T8	T10	T10	T6	T7	T6	T9	T8
Total Motor ASIA **	50	50	50	50	50	50	50	50	50	50
Period of neurological impairement (Years)	14	9	7	9	10	6	6	13	8	6
Time interval between impairment and NMES (Years) ***	11	1	5	5	9	1	5	3	4	3
Time interval of NMES (Years)	3	8	2	4	1	5	1	10	4	3

* **Auto** – Car Crash; **FAP**- Fire Arms Projectile; **TB**- Vertebral Tuberculosis

** **ASIA** - American Spinal Injury Association

*** **NMES** – Neuromuscular Electrical Stimulation

Table 3

Roentogenographic Measurements of Sagittal Alignment From Upright Paraplegic Patients Under Three Electrode Configurations of Neuromuscular Electrical Stimulation

Variables	Electrode Configuration 1		Electrode Configuration 2		Electrode Configuration 3	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Thoracic Kyphosis (T4-T12)	35,8°	7,5°	36,7°	11,7°	37,6°	9,8°
Lumbar Lordosis (L1-L5)	−46,6°	4,9°	−45,9°	6,9°	−49,4°	6,3°
Lumbosacrum Lordosis (L1-S1)	−46,4°	5°	−45,1°	44,2°	−63,6°	3,5°
Segmentar Lumbar Lordosis: L1-L2	− 8,5°	3,1°	−6,5°	2,9°	−7,4°	2°
L2-L3	− 10,8°	1,9°	−8,6°	2,2°	−8,7°	2,7°
L3-L4	−15,7°	6,4°	−15°	4,2°	−13,6°	5,1°
L4-L5	−20,8°	6,1°	−22,8°	3,8°	−24,5°	5,9°
L5-S1	−20,5°	7,5°	−24,6°	7,1°	−22,2°	5,1°
Ratio Kyphosis T4-T12/Lordosis T12-PR	0,3	0,1	0,4	0,1	0,4	0,1
Sacral Slop (SS)	60°	9,2°	59,2°	11,9°	57,4°	10,4°
Pelvic Incidence (PI)	45,4°	9,3°	47,1°	9,1°	42°	5,7°
Pelvic Tilt (PT)	15,9°	14°	11,9°	15°	9°	18,4°
Lumbopelvic lordosis PR-T12	−97,8	10,2°	−99,1°	10,3°	−105,5°	11,9°
Horizontal Distance (C7-S1) - cm	15,9	7,5	14,9	7,2	13,1	5,1
Horizontal Distance (C7-HA)- cm	19,5	10	17,2	10	15,7	8
Horizontal Distance (T4-L4)-	8	6,5	7,4	6,4	6,9	5,9

Variables	**Electrode Configuration 1**		**Electrode Configuration 2**		**Electrode Configuration 3**	
	Mean	**Standard Deviation**	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**
cm						
Horizontal Distance (T4-HA)-cm	14,1	11	11	11,2	10,8	8,6
Spinal Tilt: (S1 Horizontal line × C7-S1 line)	74,3°	8,3°	75,7°	9,7°	75,6°	5,1°
Spine-Sacral angle: (S1 end Plate × C7-S1 line)	18,4°	13,1°	13,8°	8,6°	13,6°	6,9°
Sagittal Tilt	12,7°	9,2°	8,5°	10,8°	8,4°	8,1°

Table 4

Wilcoxon test and the influence of different electrode configuration of neuromuscular electrical stimulation on the sagittal profile of the spine.

Variables	Measurements					
	RX1 × RX2		RX1 × RX3		RX2 × RX3	
	Estatistic T	P-value	Estatistic T	P-valus	Estatistic T	P-value
Horizontal Distance (C7-S1) - cm	9,5	> 0,05	9,0	> 0,05	7,5	**< 0,05 Sig.**
Thoracic Kyphosis (T4-T12)	21,0	> 0,05	19,0	> 0,05	22,0	> 0,05
Lumbar Lordosis (L1-L5)	24,5	> 0,05	12,5	> 0,05	7,0	**< 0,05 Sig.**
Lumbosacrum Lordosis (L1-S1)	18,0	> 0,05	10,0	> 0,05	5,0	**< 0,05 Sig.**
Sagittal Tilt (Vertical line × T9-HA)	5,0	**< 0,05 Sig.**	3,0	**< 0,05 Sig.**	26,5	> 0,05
Sacral Slop (SS)	20,5	> 0,05	9,5	> 0,05	14,5	> 0,05
Pelvic Incidence (PI)	24,5	> 0,05	9,0	> 0,05	8,0	**< 0,05 Sig.**
Pelvic Tilt (PT)	5,0	**< 0,05 Sig.**	23,0	> 0,05	15,0	> 0,05
Sacrum-Femur angle: (SFA)	27,5	> 0,05	16,5	> 0,05	19,0	> 0,05
Horizontal Distance (C7-HA)- cm	8,5	> 0,05	6,0	**< 0,05 Sig.**	9,0	> 0,05
Segmentar Lumbar Lordosis: L1-L2	11,5	> 0,05 NS	20,0	> 0,05	17,0	> 0,05
L2-L3	6,0	**< 0,05 Sig.**	8,0	**< 0,05 Sig.**	26,5	> 0,05
L3-L4	27,0	> 0,05	25,0	> 0,05	15,0	> 0,05
L4-L5	18,5	> 0,05	8,5	> 0,05	18,0	> 0,05
L5-S1	3,0	**< 0,05 Sig.**	22,5	> 0,05	20,0	> 0,05
L4-S1	11,5	> 0,05	14,0	> 0,05	17,5	> 0,05
Lumbopelvic lordosis PR-T12	0,0	**< 0,05 Sig.**	6,0	**< 0,05 Sig.**	42,0	> 0,05
Horizontal Distance (T4-HA)- cm	3,0	**< 0,05 Sig.**	7,0	**< 0,05 Sig.**	25,0	> 0,05
Horizontal Distance (T4-L4)- cm	21,0	> 0,05	17,0	> 0,05	26,0 >	0,05
Ratio Kyphosis T4-T12/Lordosis T12-PR	9,0	> 0,05	4,0	**< 0,05 Sig.**	14,0	> 0,05
Spinal Tilt: (Horizontal × C7-S1)	18,0	> 0,05	19,0	> 0,05	27,0	> 0,05

Variables	**Measurements**					
	RX1 × RX2		**RX1 × RX3**		**RX2 × RX3**	
	Estatistic T	**P-value**	**Estatistic T**	**P-valus**	**Estatistic T**	**P-value**
Spine-sacral angle: (S1 end plate × C7-S1) **Sig** - statistically significant	22,0	> 0,05	23,0	> 0,05	21,0	> 0,05